STScI-NGST-R0015

Space Telescope Science Institute
Next Generation Space Telescope Mission

Some Considerations for NGST Focal Plane Array Electronics Requirements

15 November, 2001

Issue A

REVISION HISTORY

ISSUE	DESCRIPTION	DATE
A	Initial release	15 November 2001

Next Generation Space Telescope Mission

Some Considerations for NGST Focal Plane Array Electronics Requirements

November 15, 2001

PREPARED BY: Bernard J. Rauscher et al.

NAME

ORG.

Bernard Rauscher

SIGNATURE

11/15/01

DATE

NAME

ORG.

SIGNATURE

DATE

APPROVED BY: Peter Stockman /BJR

SIGNATURE

Hervev S. Stockman

NAME

NGST Division Head

TITLE

Some Considerations for NGST Focal Plane Array Electronics Requirements

From: B. J. Rauscher, G. A. Kriss, M. Regan, & D. Figer
Date: 14 September 2001, Revised 14 November 2001

Abstract

Detectors for NGST are still at an early stage of development and optimum methods for operating them are still to be investigated in the ultra-low background test programs. Based on prior experience with IR detector arrays, we summarize here some operational considerations and readout modes that should be accommodated by the requirements for the NGST focal plane array electronics. At this early stage, these requirements should be as broad and as flexible as possible so that changes can be readily accommodated when informed by the test program for the flight detectors.

1 Introduction

Optimal operation of the NGST detectors can yield benefits for scientific performance that are equivalent to an increase in the area of the primary mirror. Given the early stage of development of the detectors, and the fact that the flight detector architecture will not be selected until 2003, requirements for the NGST focal plane array electronics should be broad enough to cover a wide range of operational possibilities. In this document, we summarize operational considerations and various readout modes that we believe should be accommodated by the electronics based on prior and current experience.

We do not anticipate that all of these modes need or should be enabled for flight operations. Future testing of the detectors in the lab, and of the scientific instruments, should be directed toward defining the optimum operational configurations and modes required to carry out the NGST science program. Since many features of the new detector systems have yet to be tested and evaluated, it is likely that our list is incomplete. To accommodate this possibility, we summarize areas of risk that should specifically be addressed in the detector-testing program.

In our discussions, we will use the following terminology.

READ (vb)	The act of clocking and digitizing pixels in an SCA. In this document, the word ÒreadÓ is a verb.
SAMPLE (n)	The result of a single ADC conversion. For the special case of Fowler Sampling, this is a Frame (see below) for which each pixel in the SCA has been selected and digitized once.
FRAME (n)	The result of sequentially clocking and digitizing all pixels in a rectangular area of an SCA. "Full frame readout" means to digitize all pixels in an SCA, including reference pixels. "Sub frame readout" might mean for example to

digitize only a 128x128 pixels[2] area. Under this definition, a "Fowler Sample" is a special type of FRAME.

EXPOSURE (n) The end result of Sampling-Up-the-Ramp (SUTR), Fowler Sampling, CDS, etc. This is a unit of data for which signal is proportional to intensity.

EXPOSURE TIME (n) The time argument in the expression $N_{e^-} = f \; t_{\text{exposure}}$, where N_{e-} is the number of electrons collected, f is the detected flux in electrons per second, and t_{exposure} is the exposure time in seconds.

2 General Detector Operations Issues

Detector performance depends on properties of the detector, properties of the control electronics, properties of the local environment, and properties of how the detector is operated. These four classes of properties are correlated with each other and determine the sensitivity of the detector. Ideally, one would optimize individual variables within these categories so that total system performance is optimized.

The detector vendors are optimizing the properties of the detector, GSFC is designing the control electronics and investigating the radiation environment at L2, and STScI/UR/UH (along with others) are working on how the detectors will be operated. It is important that those working on designs in any of the four categories be in close contact with each other in order to ensure optimal system design.

2.1 Use of Reference Outputs (differential inputs or extra data line)

Reference voltage levels provide a way to subtract common mode drifts experienced by all the signals in the detector. They can be provided as Òreference pixelsÓ that appear in the data stream just like any other pixel but are electronically connected to stable voltage references in the detector and are not sensitive to light.

These reference pixels can only be sensed at discrete intervals in time, say after reading all the active pixels in a single row. Alternatively, the reference voltage can be provided on an independent reference output line. In this case, these voltage levels can be sensed at any time, even while reading active pixels on other outputs. There will be subtle differences in detector performance depending on whether one is using reference pixels or a reference output and depending on the noise characteristics (noise power spectral density function) of the detector and electronics. Given that we do not know whether the NGST flight detectors will have reference pixels, reference outputs, and/or possibly both, and given that we do not know the noise characteristics of the detector or associated electronics, it is important to preserve the greatest possible flexibility in the electronics and operations software.

The final decision as to how to use reference voltage levels will have a very strong influence on the electronic hardware design, i.e. in the form of differential inputs, or in clamp-and-hold circuits, etc.

2.2 Idle Patterns

An ÒidIe patternÓ refers to the clocking sequence that controls a detector while it is not being used for an exposure. It can serve to ensure that the detector wells do not fill up and induce persistent charge in science or calibration exposures. Or, it can serve to stabilize the detector temperature by keeping the power through the detector relatively constant during and between exposures. The idle pattern might be a sequence of resets, although the exact pattern of resets or the numbers of lines that get reset is not known without experimenting with detectors that have the same design as the flight detectors. In addition, it is not clear which biases should be turned on during idle mode.

Guidelines

1 The controller should offer a user-selectable option to idle the array in a manner TBD.
   1.1 Between exposures
   1.2 During an exposure when pixels are not being sampled (e.g., between the first and second groups of Fowler Samples during Fowler Sampling).
2 Downlink options should include the following.
   2.1 None

2.3 Clocks/Biases

The two vendors differ on the number of clocks and biases that must be provided, the bias/clock voltage levels, and the stability required. At this stage, the electronics must accommodate these uncertainties.

Guidelines

1 The controller should provide enough clocks and biases to accommodate either vendor.
2 All clocks and biases should be adjustable over the voltage range consistent with the needs of both vendors.
3 Clocks and biases should be sufficiently stable (TBD) to meet the noise and other requirements in NGST Doc. 641.

2.4 Number of ADC Bits and Gain

Under the assumption that NGST should be limited by the telescope background, or by the detectors themselves when this is not possible (e.g., some spectroscopy), 16 bits (and two gain settings; ~1 e^-/ADU & ~3 e^-/ADU) are required to represent the full signal range for both the NIR and MIR .

There are three key inputs to this argument. From NGST Doc. 641, these are the total system noise goal = 3 e- rms, detector noise goal = 2.5 e-, and well depth goal = $2x10^5$ e-. Assuming that A/D errors and detector noise are uncorrelated, these components add in quadrature and the required gain is about 1.66 e-/ADU. The full well value of $2x10^5$ e- corresponds to $1.2x10^5$ ADU, which cannot be represented with less than 17 bits. Adding 1 bit for ADC uncertainty yields ~18 bits.

Applying this logic, 18 bits would be needed to meet both the NIR and MIR detector goals if only one gain setting were available. Fortunately, an attractive alternative exists to allow the use of a 16 bit A/D with the implementation of selectable gain on the A/D preamplifier. This approach is the recommended strategy for the current design. We recommend providing at least 2 gain settings with the precise gain settings chosen to allow full wells $=6\times10^4$ e^- and 2×10^5 e^- (TBR). Up to two additional gain settings (bringing the total up to 4) may optionally be provided to allow for finer digitization of low-noise detectors.

Guidelines

1 Electronic gain g~1 e-/ADU for small signals.
2 Largest signal =200,000 e-[1].
3 Clocks and biases should be sufficiently stable (TBD) to meet the noise and other requirements in NGST Doc. 641.
4 The data system should unambiguously assign monotonically increasing data values to increasing SCA signal levels.

3 Read-out Modes

3.1 Methods for Sampling Pixels

In addition to the ÒnormalÓ way of reading an array: clock to a pixel, wait for output to settle, sample the pixel, clock to the next pixel, etc., we may want to sample the pixel more than one time (after it has settled) before we proceed to the next pixel. This would be an option that applies to all read modes since read modes specify how we want to sample the whole frame. This mode can remove certain types of noise on time scales that reading the whole frame cannot. The pseudo-code for reading the pixel would be:

```
integer read_pixel(number_of_multiple_reads)
integer number_of_multiple_reads;
{
   wait_for_pixel_to_settle();
   for (i=1; i++; i<=number_of_multiple_reads){
      sum += sample_adu;
   }
   sum = sum >> TBD bits[2]
 return(sum);
}
```

At this point in time, it is not necessarily clear that 12 μs is the optimal sampling time for NGSTÕs SCAs. For example, shorter timescales might allow NGST to implement digital filtering in lieu of more traditional RC filtering for bandwidth limiting. The ProjectÕs test labs are set up to explore sampling times other than t=12 μs.

When dwelling on a pixel to execute more than one sample, it would be permissible to remain on that pixel for longer than t=12 μs (there is no requirement on the maximum dwell-time). Additionally, we recommend that it be possible to sample each pixel 1, 2, 4, 8, 16, 32, or 64 times before moving onto the next pixel. Dwell time on each pixel would be a function of the number of samples. We envision that the number of samples per pixel would be constant for all pixels in an exposure.

---

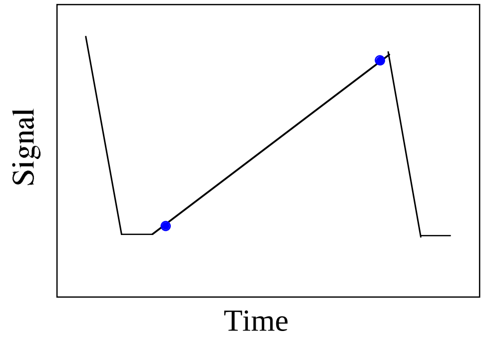
[1] With NGST Detectors, the noise in a signal =200,000 e^- would be strongly dominated by Poisson statistics on the detected photons. We recommend that the electronics degrade this noise by no more than 10% when added in quadrature. For these bright-source observations the tolerable read noise is much larger being about $\sigma_{read} < 204\ e^-$.

[2] The aim of this shift is to preserve the 16 most significant bits, without roundoff error, in the data that are provided to the astronomer (TBR).

3.2 Correlated Double Sampling

Correlated double sampling (CDS; see box at right) is a technique whereby each pixel is reset, and then sampled at the beginning and end of integration. Correlated double sampling differs from Fowler-1 Sampling in that data samples may be taken immediately after a row is reset. CDS is most useful for background limited imaging.

For NGST however, at this early stage in the design CDS may be regarded as Fowler-1. Although subsequent detector testing may show that subtle differences between Fowler-1 and CDS should be allowed for, we anticipate that the primary impacts would be on software.



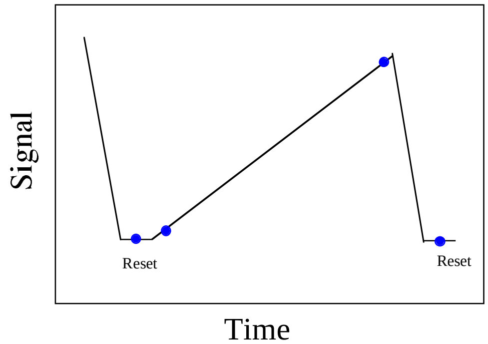
Correlated Double Sampling

Guidelines

1 The controller should enable correlated double sampling with the following reset options.
   1.1 Global reset (all pixels in SCA simultaneously)
   1.2 Row-by-row (AKA Òripple Ó) reset with first read immediately following row-by-row reset of all pixels in the frame.
2 Downlink options should include the following.
   2.1 Difference = (final — initial)
   2.2 Debug = all data

3.3 Correlated Triple Sampling

Correlated triple sampling (CTS; see box at right) is a technique whereby each pixel is sampled while it is being reset, sampled again immediately following reset, and then at the end of integration is sampled again before finally sampling the reset level. The advantage of CTS compared to CDS is improved 1/f noise rejection (the reset level serves as a reference). Like CDS, CTS is most useful for background limited imaging. CTS also provides the necessary data for some useful debugging modes. For example, one can measure system gain by examining the first reset level. Likewise, the NGST test labs have in the past found it to be useful to examine the pedestal level which is digitized during the first sample in CTS.



Correlated Triple Sampling

Guidelines

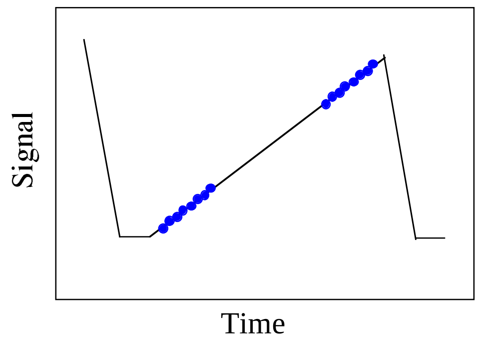
1 The controller should enable correlated triple sampling with the following reset options.
   1.1 Global reset (all pixels in SCA simultaneously)

1.2 Row-by-row (AKA Òripple Ó) reset with first read immediately following row-reset

2 Downlink options should include the following.
  2.1 Difference = (S2 - $S2_{reset}$) — (S1 — $S1_{reset}$)
  2.2 Reset = Return the first sample of the Reset level
  2.3 Pedestal = Return the first sample on the ramp, immediately following reset
  2.4 Debug = all data

3.4 Fowler Sampling

Fowler Sampling (see box at right) is a technique using multiple non-destructive reads to average over white noise components. In Fowler Sampling, rms noise diminishes as $1/\sqrt{n}$, where n is the number of Fowler Samples. Fowler Sampling begins to break down when non-white noise components become significant.



Fowler-8 Sampling

Guidelines

1 The controller should enable Fowler Sampling as specified below (TBR), where t = integration time and n = number of Fowler Samples. Read_frame() is a function using full-frame arithmetic that should be implemented in a manner consistent with section 4.

```
/* Take a Fowler Sampled exposure */
Fowler_exposure(t) {
      Reset_array;
      Fowler_sum1 = Fowler_sum2 =  0;
      For (j=0; j<n; j++)
            Fowler_sum1 += Read_frame;
      }
      Send_to_SSR(Fowler_sum1);
      wait(t);
      For (j=0; j<=n; j++)
            Fowler_sum2 += Read_frame;
      }
      Send_to_SSR(Fowler_sum2);
}
```

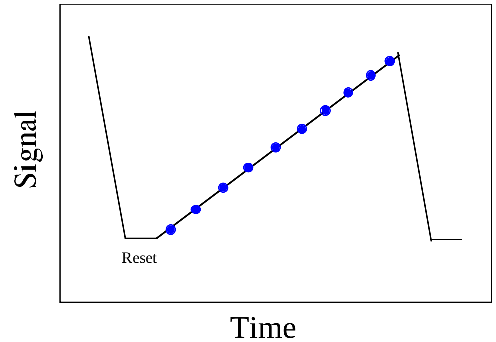
2 The number of Fowler Samples, n, should be user selectable from the set n $\in$ {1, 2, 4, 8, 16, 32, or 64}.

3 Downlink options should include the following.
  3.1 average of initial samples and average of final samples
  3.2 difference = (final average — initial average)

3.3 Debug = all data

3.5 Up-the Ramp Sampling

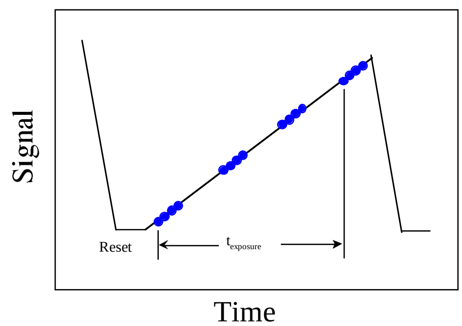
In up-the-ramp mode (see box at right) the array is read out at intervals during the exposure. In this mode the value that is returned for each pixel is the count rate (ADU/sec) for each pixel. This rate can be determined by computing the weighted sum of the individual reads. The optimum weight to use depends on the signal level relative to the read noise. Therefore, the weight table to use needs to be variable. Also, the interval between the reads of the array needs to be variable.



Sampling-Up-the-Ramp

3.6 Multi-Accum Sampling

In multi-accum mode (see box at right) the array is read out non-destructively at intervals over the exposure. These intermediate reads are then down-linked. The advantage of this mode is that cosmic rays can be rejected on the ground and data before and after a cosmic ray hit is still useable. This allows longer effective exposure times and a large increase in the signal to noise ratio.



Multiaccum

In this mode there are three unique variables: m, the number of reads in a Fowler burst; n, the delta time between Fowler bursts; and t the total integration time. The mode operates by averaging the m reads every n seconds and down-linking the result. Once the total time has reached t seconds then the operation stops.

```
Reset_array;
For (j=0; j<=t/n; j++){
  For (i=1;i<=m; i++){
    Array_sum += read_array(number_of_multiple_reads);
  }
  Result=Array_sum/m;
  Send_to_SSR(Result);
  Wait(n);
}
```

3.7 Subarrays Readout

Most IR photometric calibration standards are too bright for observation in a minimum integration time of 12 s. These calibration observations are essential for achieving the scientific goals of the entire DRM. In addition, although the DRM is dominated by observations of faint objects, there are programs for observations of galactic objects in which the objects themselves or reference field objects are brighter than can be observed in a full-array minimum integration time of 12 s. Subarrays that permit shorter integration times should be enabled in a manner consistent with the wavefront sensing requirements specified in NGST Document 641.

Since it may not be possible to achieve short integration times while simultaneously reading the reference pixels, the correlated triple sampling read mode described above combined with subarray capability could potentially provide the necessary sampling of the reference voltage levels to reduce 1/f noise.

We note that an operational mode for the flight software and the ground system could be defined in which a pattern of contiguous subarrays is exposed in a serial fashion. This would permit observations using a large portion of the FPA but using short exposures times.

4 Using Reference Pixels

Reference pixels are specially engineered pixels that are unresponsive to light, but that in other ways are designed to mimic a real pixel. If properly used, reference pixels have the potential to enable NGST to relax electrical and thermal stability requirements by an order of magnitude or more. Moreover, they potentially may allow NGST to avoid detector stability problems that have plagued other space instruments, e.g. the NICMOS ÒPedestal EffectÓ and SIRTF/IRACÕs ÒFirst Frame Effect.Ó

Although it is too early to say specifically how reference pixels will be used, it is clear that data from a large number (>~100) pixels will need to be combined in order to avoid adding noise to the data. Operations that aim to fit structure in frames would ideally be performed on a Frame-by-Frame (or Fowler Sample by Fowler Sample basis). At this point in time however, it appears unlikely that flight electronics can support this level of flexibility. For purposes of this document, we recommend that reference pixels be treated in precisely the same manner as any other pixel. More sophisticated spatial-averaging and any other processing would be performed on the ground. The electronics should make no special provisions for reference pixels beyond ensuring that they are read out with the data in the same manner as any ÒnormalÓ pixel.

Guidelines

1 The control electronics should read and process reference pixels in precisely the same manner as ÒnormalÓ light-sensitive pixels.

2 The controller should downlink reference pixels to the ground along with all of the ÒnormalÓ light-sensitive pixels.

5 Integration Times

Integration times should be flexible. They should range from a minimum of 12 s, the shortest possible time in which one can read a whole FPA, to a maximum as large as 65000. The latter number is much higher than has been previously discussed, but there are scenarios in which a Multi-Accum readout with individual intervals of 250-1000 s and a total integration time of tens of thousands of seconds would yield the best results.

Integration times shorter than 12 s should be allowed when reading subarrays from a specific SCA. Under this scenario, the controller should enable sub-array readout as specified in NGST Doc. 641 for wavefront sensing. For maximum flexibility, intermediate frame sizes (between full-frame and wavefront sensing sub-arrays) and exposure times should be supported.

6 Risk Mitigation

This section is closely paraphrased on section 6 of Boyce et al. (2001). The following working list of items requiring additional experimental or analytical study has emerged from the deliberations of the Boyce et al. (2001) team, consultation with the NGST test labs, and from an earlier Detector Requirements study. These data must be taken under anticipated NGST conditions. Specifically, these conditions include NIR array temperatures near 30 K (~6 — 8 K for the MIR range), low-background flux (extremely low, in the case of the highest-resolution spectroscopic measurements), and extended integration times of up to 10s of thousands of seconds.

6.1 Noise

i. Studies of the spectral noise content of arrays, and experimental comparisons of sampling schemes (including Fowler, sample-up-the-ramp, & possibly others or variations). The parametric dependence of FET noise upon temperature, bias/current, and sampling factors (especially the time interval between samples, the total number of samples, and the specific averaging or weighting algorithms) must be determined.

ii. Studies of noise contributions from dark current: This will involve accurate measurements of the magnitude of dark current, and then the characterization of the noise contribution arising from these integrated charge samples. In particular, data are needed to ascertain if noise from dark current follows Poisson statistics.

iii. Additional noise factors: Careful, quantitative studies of non-white noise components including (but not necessarily limited to) bias drift ("pedestal effect"), shading, and Ôbars & bandsÕare needed. In particular, it is important to determine how much of bias drift is electronic vs. thermal in origin.

iv. Studies of total noise: The overall noise level must be carefully determined, with specific interest in whether all contributing factors have been identified and whether these combine as theory predicts.

6.2 Other Parameters

i. Additional resets or throwaway frames. Data are needed to determine the extent to which periodic resets will be needed, and how many throwaway data frames might be needed, under typical long-exposure conditions. These strategies are expected to restore stable operation to arrays, after a transient imposed by, for example, a slew to a location with a significantly different illumination level, a solar flare incident, a focal plane temperature excursion, a power transient, etc.

ii. Reference pixels. Careful studies are needed to characterize the noise and stability of the reference inputs (e.g., on-chip capacitors mimicking detectors) being designed into current-generation candidate arrays. Techniques for best utilizing these inputs need to be developed and tested, with specific interest in how total noise is affected.

iii. Sub-array readout. Experimental data are needed to verify that sub-array readout is practical. Concerns include the possible presence of synchronous noise, glow effects (due to the higher current draw implied by higher frame rates), potential limitations on the ability to access an arbitrary field within the array, etc.

iv. Driving exit cables. The focal plane outputs must be driven over ~6-m of cable to reach the first stage of amplification. It is important to test the ability of the output driver FETs on candidate FPAs to deliver signals over a simulated ISIM exit cable (with characteristics such as length, capacitance, and conductor geometry / shielding consistent with baseline ISIM designs). These data should indicate whether intermediate-temperature line-driver amplification must be included in the ISIM design. Key measurements will include noise, pickup, and transient response.

v. Power dissipation. Measurements are needed of power dissipation resulting from various candidates operating modes and sampling schemes. (Although this is primarily a driver for cryogenic and thermal control subsystem designs, the achieved dissipation levels couple to the data system design, in limiting number of samples, rate of samples, etc.)

vi. Cosmic Rays. Data are needed of the sensitivity of the detector technologies to cosmic rays, including the amount of charge which bleeds into adjacent pixels, the time history of the release of charge due to cosmic rays, and the effectiveness of resets at removing cosmic rays. The Goddard Radiation Effects and Analysis Group (REAG) has begun a study of radiation effects on IR arrays.

The three ultra-low background test labs have plans for testing all of the above with the exception of driving long exit cables.. Plans for exit-cable testing have not been finalized, but it is very likely the appropriate capability will exist through a collaboration between the Goddard engineers working on the harness and the STScI test lab. The detector development contracts are producing sample arrays, and this will continue at an increasing pace.

Given the wide range of potential array characterization parameters, it is essential that specific test plans and specifications, which specifically address these ISIM data system issues, be negotiated and instituted with the appropriate test teams.

7 References

L. Boyce et al. 2001, ISIM Detector Readout Reference Design: Cycle 1, Goddard Space Flight Center